

The University of Chicago

A STUDY OF
CERTAIN CHARACTERISTICS OF
STELLAR SPECTRA OF TYPE A

A DISSERTATION SUBMITTED TO THE GRADUATE
FACULTY IN CANDIDACY FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS

By
WILLIAM WILSON MORGAN

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STUDIES IN PECULIAR STELLAR SPECTRA

I. THE MANGANESE LINES IN α ANDROMEDAE

By W. W. MORGAN

ABSTRACT

The strong lines of *ionized manganese* which in the past have been observed only in the spectrum of α Andromedae have been found in *thirteen other stars* of spectral classes B5-A0. It is fairly certain that the *stage of ionization is the second (Mn III)*. In the light of the present observations the *behavior of ionized manganese* in stellar spectra seems to be *entirely normal*.

1. The predictions of the general theory of ionization, developed by M. N. Saha, R. H. Fowler, E. A. Milne, and others, are usually so closely in accordance with observation in stellar spectra that it is of some importance to determine whether the few apparently anomalous cases reported by various observers are real. As it now seems fairly certain that the stars in general have about the same relative abundance of the different elements, those stars which do not fit into the two-dimensional scale of temperature and pressure are of especial interest. Among the early A stars there are several groups which have seemed at one time or another not to be in accordance with the ionization theory. These are: (1) the *c*-stars, or supergiants; (2) stars in which the *Si II* doublet 4128 and 4131 is strong; (3) stars in which the ultimate *Sr II* lines 4077 and 4215 are of considerable intensity; (4) 12 α^2 Canum Venaticorum; (5) stars which resemble 37 θ Aurigae; (6) 21 α Andromedae. All representatives of the foregoing groups which have been classified in the *Henry Draper Catalogue* are designated as peculiar.

A few supergiant stars in the range A0-A5 which have very narrow, deep lines were formerly supposed to be in a small class by themselves. It is now thought, however, that their spectra fit in the ordinary scale of temperature. The increased intensity of the lines can be accounted for on the basis of thermal ionization.

The great strength of the *Si II* doublet 4128 and 4131 was formerly considered to be anomalous. It now seems that singly ionized silicon reaches a normal maximum at A0 and that the intensities of its lines are normal. The problem has, however, not as yet been fully investigated.

There are a few A-type stars in which the Sr II lines 4077 and 4215 are very strong. As these lines normally reach their maximum at about K5, they should be weak, if present at all, in A stars. The lines are very sensitive to changes in absolute magnitude as they become much stronger on passing from dwarfs to giants. This effect of absolute magnitude will possibly explain the apparently abnormal intensities in some A stars.

The spectrum of $\iota_2 \alpha^2$ Canum Venaticorum was found in 1900 by Sir Norman Lockyer and F. E. Baxandall¹ to contain a large number of strange, unidentified lines. Many of these lines were later identified by Baxandall² as being due to the rare earth europium. C. C. Kiess³ later provisionally identified a number of the other lines as being due to terbium. The spectrum of $\iota_2 \alpha^2$ Canum Venaticorum has also been studied by H. Ludendorff,⁴ A. Belopolsky,⁵ Miss C. Anger,⁶ and by A. Markov.⁷ The spectrum of $36 \tau^9$ Eridani was described by O. Struve and C. Hujer⁸ as being similar to that of α^2 Canum Venaticorum.

Lockyer and Baxandall⁹ also announced in the spectrum of 37θ Aurigae the presence of a number of well-marked lines which they were unable to identify. The *Henry Draper Catalogue* lists a few other stars as having spectra similar to that of 37θ Aurigae. The spectrum of 37θ Aurigae is given by the same authority as Aop.

Lockyer and Baxandall¹⁰ gave the positions of a number of strange lines in the spectrum of α Andromedae. In a later paper Baxandall¹¹ identified most of these lines with those in the spark spectrum of manganese. This star has heretofore been considered abnormal and as almost unique in the intensity of the manganese lines.

¹ *Proceedings of the Royal Society of London*, A, **77**, 550, 1906.

² *Monthly Notices*, **74**, 32, 1913.

³ *Publications of the Observatory, University of Michigan*, **3**, 106, 1923.

⁴ *Astronomische Nachrichten*, **173**, 1, 1926.

⁵ *Bulletin de l'Académie Impériale des Sciences de St. Pétersbourg* (series vi), **7**, 689, 1913; also *Astronomische Nachrichten*, **196**, 1, 1913, and *ibid.*, **234**, 93, 1928.

⁶ *Astrophysical Journal*, **70**, 114, 1929.

⁷ *Ibid.*, **72**, 301, 1930.

⁸ *Ibid.*, **65**, 300, 1927.

⁹ *Proceedings of the Royal Society of London*, A, **77**, 550, 1906.

¹⁰ *Ibid.*

¹¹ *Monthly Notices*, **74**, 250, 1914.

The stars 12 α^2 Canum Venaticorum, 37 θ Aurigae, and 21 α Andromedae are thus three of the most striking misfits in the thermal ionization sequence. The present paper is concerned with the study of the ionized manganese lines which were first found in α Andromedae. It was my purpose to ascertain whether or not the presence of these lines is really "abnormal" from the point of view of the modern theory of ionization.

2. The original discovery, by Lockyer and Baxandall, of a number of strong, unidentified lines in the spectrum of α Andromedae was made in 1906. The plates taken by them at South Kensington seemed to show slight changes in the relative intensity, position, and definition of some of the lines. In Lockyer's system of spectral classification, α Andromedae was placed in the "Markabian" group for which 54 α Pegasi is the standard star, located midway between Sirius (A0) and Algol (B8). Because of the strength of the helium lines, α Andromedae was placed closer to Algol in temperature than to Sirius. The most prominent of the strange lines were at $\lambda\lambda$ 3943.8, 3984.0, 4136.9, 4206.3, and 4282.4 Å. In 1913 Baxandall identified these lines, with the exception of 3984.0, with enhanced lines in the spectrum of manganese. Many other fainter lines were also found to be due to the same source. Attention was called to the fact that the relative intensities of the lines are not the same as in the laboratory. The line showing the greatest inconsistency was at 4344.04, which is of intensity 8 in the laboratory. In α Andromedae the lines 3943.78, 4137.01, 4206.41, and 4325.67 are all much stronger than 4344.04. The explanation given is that the difference in relative intensity is probably due to different conditions in the star from those in the laboratory. It does not seem necessary, however, to use this explanation, because the line 4344.04 occurs in the wing of $H\gamma$ at 4340 and for this reason is certainly greatly weakened.¹ A list was given of six lines in the spectrum of 50 α Cygni and of six lines in 9 α Canis Majoris which were possibly due wholly or in part to "proto-manganese."

¹ The weakening of lines in the wings of the very broad hydrogen lines is due to the increased opacity of the stellar material due to absorption by hydrogen. In a wavelength in the wing of a Balmer line we do not see as deeply into the reversing layer as we do in the continuous spectrum (see Unsöld, Struve, and Elvey, *Zeitschrift für Astrophysik*, 1, 314, 1930).

The spectrum of α Andromedae is given as Aop in the *Henry Draper Catalogue* with the remarks, "The spectrum is very peculiar. It resembles Class Ao in respect to the hydrogen and calcium lines, while lines 4026.2, 4267.4, and 4471.5 are of the same intensity as in Class B8. Several strong solar lines are present." The *Henry Draper Catalogue* contains one other bright star, 5μ Leporis, which is noted as being similar to α Andromedae, but no further details are given.

The Mount Wilson revision of Rowland's *Preliminary Table of Solar Wave-Lengths* records a number of lines as being due to Mn II. One multiplet of singly ionized manganese has been picked out by M. J. Catalan in the far ultra-violet. This multiplet is well marked in the sun. Almost all of the other suggested identifications with Mn II are marked as questionable. T. Dunham, Jr.,¹ has listed a few lines in the spectrum of 33 α Persei as being possibly partly due to Mn II. Miss E. T. R. Williams² states that ionized manganese may be present in the spectrum of 9 α Delphini.

If the hydrogen lines and the H and K lines of ionized calcium be excluded from consideration, the spectrum of 21 α Andromedae resembles closely the spectrum of a normal B8 star except for the presence of the manganese lines and of a few other unidentified lines. The helium lines 4026 and 4472 are well marked; He 4144 and 4387 are easily visible, and, on the best Yerkes plates, 4121 is certainly present, although extremely faint. The singly ionized carbon line 4267 is equal in intensity to Fe II 4233. The Si II doublet 4128 and 4131 is fairly strong. Several of the strongest lines of Fe II are present. Between the limits 4000 and 4650 are the following Fe II lines: 4178, 4233, 4303, 4351, 4416, 4508, 4515, 4549, 4555, 4583, and 4629. Most of these lines are near the limit of visibility. Except for Mg II, 4481, the other singly ionized metals seem to have almost entirely disappeared. With the exception of the helium lines and carbon 4267, the high-temperature lines of type B do not appear. All of the lines in the spectrum are slightly diffuse, probably as a result of rotation of the star. The spectrum is, however, of fair quality.

Because of the general faintness of the metallic lines and the strength of helium, it seemed probable that the most promising place

¹ *Contributions from the Princeton Observatory*, No. 9, 1929.

² *Harvard Circular*, No. 348.

to search for other stars containing manganese lines would be in the range of classes B₅-A₀. During the last thirty years spectra of practically all B and A stars brighter than magnitude 5.5 and north of about -25° declination have been obtained with the Bruce spectrograph attached to the 40-inch telescope of the Yerkes Observatory. A search was made through all of the stars of which measurable plates have been obtained in the range B₅-A₀ inclusive. Only one-prism plates were used, as Yerkes three-prism spectra do not extend farther into the violet than about 4300, and almost all of the ionized manganese lines are to the violet of this limit. I have examined the spectra of 362 stars on an average of about five plates for each star. Besides 21 α Andromedae and 5 μ Leporis, 12 other stars

TABLE I

Spectrum (H.D.)	No. of Stars Examined	Manganese Stars	Per Cent Mn Stars
A ₀	197	4	2.0
B ₉	38	4	10.5
B ₈	69	4	5.8
B ₅	58	2	3.4

were found which definitely showed some or all of the lines of manganese. Table I gives the number of manganese stars found as compared to the total number examined in each spectral subdivision. The percentages listed in the last column are small, owing, no doubt, to the faintness of the manganese lines. Many of the stars examined have very broad and hazy lines, believed to be such on account of rapid axial rotation of the stars. Since rotation very materially reduces the central intensity of a narrow line, it is clear that such faint lines as these of manganese will not be visible in stars with rapid rotations. It is therefore more representative to exclude the stars with rapid rotations (character of lines "Few, poor" on the Yerkes classification; see *Publications of the Yerkes Observatory*, 7, Part I, and *Astrophysical Journal*, 64, 1, 1926). The results are shown in Table II.

Table III lists the fourteen stars which show the lines clearly in order of right ascension. The last column of the table gives the estimates of the number and quality of the lines in the spectrum of each

star. These estimates were made a number of years ago in connection with measures for radial velocity and were used as a criterion of the order of accuracy to be expected. The Yerkes plates of α Delphini, although of good quality, do not seem to confirm the presence of ionized manganese as suspected by Miss Williams. The spectral

TABLE II

Spectrum (H.D.)	No. Stars Less "Few, poor"	Manganese Stars	Per Cent <i>Mn</i> Stars
Ao.	110	4	3.6
B9.	22	4	18.2
B8.	35	4	11.4
B5.	35	2	5.7

TABLE III

Star	α 1900	δ 1900	Magnitude	Spectrum (H.D.)	Character
21 α Andromedae.	$\alpha^{\text{h}03^{\text{m}}}$	$+28^{\circ} 32'$	2.2	Aop	Ff
$+59^{\circ} 146$ Cassiopeiae.	0 51	$+59^{\circ} 50'$	5.5	B9	Fg
α Sculptoris.	0 54	$-29^{\circ} 54'$	4.4	B5	Ff
53 Tauri.	4 14	$+20^{\circ} 55'$	5.4	B8	Fg
5 μ Leporis.	5 08	$-16^{\circ} 19'$	3.3	Aop	Mf
112 β Tauri.	5 20	$+28^{\circ} 31'$	1.8	B8	Ff
37 θ Aurigae.	5 53	$+37^{\circ} 12'$	2.7	Aop	Ff
23 γ Canis Majoris.	6 59	$-15^{\circ} 29'$	4.1	B5	Fg
14 Hydrae.	8 44	$-3^{\circ} 04'$	5.2	B9	Ff
76 κ Cancr.	9 02	$+11^{\circ} 04'$	5.1	B8	Mf
26 π Bootis.	14 36	$+16^{\circ} 51'$	4.9	Ao	Fg
6 ν Herculis.	16 00	$+46^{\circ} 19'$	4.6	B9	Fg
11 ϕ Herculis.	16 06	$+45^{\circ} 12'$	4.2	B9p	Mg
$+33^{\circ} 3154$ Lyrae.	18 33	$+33^{\circ} 23'$	5.5	B8	Fg

ABBREVIATIONS: Mg=Many, good

Mf=Many, fair

Fg=Few, good

Ff=Few, fair

lines are extremely broad and diffuse, probably because of a high speed of rotation. Other stars not included in Table III are suspected more or less strongly of containing ionized manganese. In some cases the plates are not of sufficiently good quality to permit certainty, and in others the lines are so extremely faint that some doubt is felt as to their reality. If fine-grain plates were available for all the stars from B5 to Ao, numerous others would almost certainly be included. Although the range in spectral type of the four-

teen stars is from B5 to A0, the actual range in effective excitation is very small. Twelve of the fourteen stars contain the helium lines 4026 and 4472, and in no case is 4472 as strong as *Mg* II 4481. As the equality of these two lines is one of the criteria for spectral type B8, it can be seen how closely the stars are grouped together as far as state of excitation is concerned. It is apparent from Table III that the percentage of manganese stars is greatest at B9. In fact, only two of the stars, 37 θ Aurigae and 53 Tauri, can really be classed as A0 if the evidence of the metallic lines and of the presence of helium is used. It is of some interest to note that apart from the rapidly rotating stars, the classification of the A0 stars into divisions of "many lines" and "few lines" is roughly a separation of stars of lower from those of higher temperature. As a rule, the stars which are classified "Mg" and "Mf" owe their increased number of lines to the appearance of a large number of metallic lines of lower temperature, both neutral and ionized. In the "Fg" and "Ff" stars, practically all of the neutral and weak enhanced lines of iron and titanium have disappeared. The A0 stars having few lines form therefore an intermediate class between the B8 and B9 stars and A0. The only A0 star found to contain manganese which was classified as having many lines is 5 μ Leporis, and the reason for its classification as "Mf" is not because the metallic lines are numerous, but because the manganese lines themselves are more conspicuous than in any other star observed. Several of the stars, such as 5 μ Leporis, 20 π Bootis, and 76 κ Cancri, are, as far as the relative intensities of the spectral lines are concerned, almost identical with α Andromedae.

3. All of the lines attributed to "proto-manganese" by Baxandall which could be seen on Yerkes plates were measured for wave-length. Two plates were measured of α Andromedae, two of μ Leporis, and one of φ Herculis. The two plates of μ Leporis cover different parts of the spectrum and only two of the lines are duplicated. Table IV gives the measures of Baxandall and my own measures. The columns are: the laboratory wave-lengths determined by Lockyer; Lockyer's laboratory intensities in the arc and spark; wave-lengths in α Andromedae (Baxandall); wave-lengths in α Andromedae, μ Leporis, and φ Herculis (Morgan); the mean wave-lengths (Morgan). There are three manganese lines observed in

21 α Andromedae by Baxandall which I did not measure. Two of these are outside the region of best definition on Yerkes plates. The lines at 4200, 4248, and 4282 were not observed by Exner and Haschek in the laboratory, but are all certainly present in α Andromedae. The line at 4300 is given as of intensity 2 in both arc and spark, while in Lockyer's list it is given as of intensity 2 in the spark and absent in the arc. There may thus be some doubt as to

TABLE IV

LAB.	INT. LABORATORY		α AND. (BAX.)	INT.	α AND.	INT.	μ LEP.	INT.	ϕ HER.	INT.	MEAN
	Spark	Arc									
3943.78....	2	0	3943.71	4	3943.74	4	3943.92	3-4	3943.91	I	3943.86
4000.05....	2	0	4000.00	I-2	3999.93	I-2	3999.93	.....	.....	.....	3999.93
4104.90....	3	0	4105.34	?2	4105.14	4	4105.03	3-4	.....	.....	4105.11
4128.21....	2-3	.....	4128.11	4-5	4128.16	5-6	4128.07	7	4128.01	7	4128.12
4137.01....	3-4	0	4136.90	3-4	4136.88	4-5	4136.89	5	4137.02	5	4136.92
4200.25....	2	0	4200.70	I-2	4200.35	2	4200.40	3	.....	.....	4200.37
4206.41....	4	0	4206.46	3-4	4206.14	5	4206.39	5	4206.00	2	4206.17
4242.30....	4	0	4242.35	2	4242.46	I-2	4242.50	3-4	.....	.....	4242.45
4244.28....	I-2	0	4244.61	I	4244.42	I-2	.....	.....	.....	.....	4244.42
4247.95....	I	0	4247.72	2	4248.03	I-2	.....	.....	.....	.....	4248.03
4251.71....	5	0	.....	.....	.....	.....	4251.43	3-4	.....	.....	4251.43
4252.98....	5	0	4253.28	2	4253.10	3	4252.97	4	4252.79	3	4252.99
4259.20....	4	0	4258.87	2-3	4259.29	3	4259.09	4-5	.....	.....	4259.19
4282.50....	3	I-2	4282.72	2-3	4282.27	3-4	4282.35	4	4282.37	3-4	4282.31
4283.81....	I	0	4283.80	2	(4284.30)	2	(4284.32)	3	(4284.17)	3-4	(4284.26)
4292.20....	2-3	0	4292.11	2-3	4292.23	2	4292.33	3	4292.23	I-2	4292.25
4300.22....	2	0	4300.40	I-2	4300.20	I-2	4300.12	3	4300.18	4	4300.18
4326.67....	5	0	4326.64	3	4326.56	3	4326.75	4	4326.64	4-5	4326.62
4344.04....	8	0	4343.95	2	4344.04	2-3	4343.87	4	.....	.....	4343.99
4348.47....	2	0	4348.35	2	4348.69	I-2	4348.55	I-2	.....	.....	4348.62
4365.35....	I-2	0	4365.14	I	.....	.....	.....	.....	.....	.....	.....
4478.71....	2-3	0	4478.49	I-2	4478.46	I-2	4478.49	I-2	4478.56	I	4478.49
4755.74....	2	<I	4755.64	4	.....	.....	.....	.....	.....	.....	.....
4764.75....	2	0	4764.47	2	.....	.....	.....	.....	.....	.....	.....

whether it is actually enhanced in the spark. It may be that the line observed in α Andromedae is due entirely to Ti II, which has a strong line at 4300. Several other manganese lines coincide in position with enhanced metallic lines. There are Cr II lines at 4242.37, 4252.65, and 4284.20; 4343.99 may be blended with Ti II 4344.29. The strong Si II 4128.05 makes it impossible to express an opinion on the manganese line in the same position. There is an exceedingly faint line at 4136.9 in Sirius which is almost certainly due to neutral iron, but it seems impossible that this weak line could contribute sensibly to the well-marked manganese line in the same position in the hotter stars. The most distinctive of the unblended manganese lines are those at 3942.86, 4136.92, 4206.17, and 4326.62.

4. Lockyer and Baxandall¹ measured twenty-four enhanced lines in the spark spectrum of manganese. Only two of these lines are present in the arc spectrum. The list of Exner and Haschek includes a great many more lines, many of which are much stronger in the spark than any of the lines measured by Lockyer and Baxandall. It seems, therefore, that the conditions of excitation were decidedly higher in the apparatus used by the latter.

The multiplet relationships and successive stages of ionization of manganese are not known above the first stage, except for a single multiplet of $Mn II$ in the far ultra-violet which was picked out by

TABLE V
 $Mn II$ MULTIPLET

Fuchs	Int. Arc	Int. Spark	Sun	I_R	α Cygni	I_W	E.P.
3441.999.....	2	30	3441.983	6	3442.07	3+	1.768
3460.332.....	2	20	3460.327	4d?	3460.33	3-	1.802
3474.050.....							
3474.139f.....	1	15	3474.151	2	3474.14	3	1.825
3482.918.....	2	12	3482.910	5d?	3482.93	3	1.825
3488.618.....	2	10	3488.679	4	3488.67	3	1.840
3495.840.....	1	7	3495.836	2	3495.78	2+	1.847
3496.815.....	1	3	3496.814	3			1.825
3497.540.....	1	6	3497.530	3	3497.55	2-	1.840

Catalan.² The lines of the multiplet range in wave-length from λ 3442 to λ 3497 and are thus far out of the range of ordinary stellar spectrograms. The multiplet is strong in the sun, and there can be no doubt that seven strong lines in the ultra-violet spectrum of α Cygni measured by W. H. Wright³ and attributed by him to manganese form the same multiplet of $Mn II$ that is present in the sun. These lines are all strong in the arc and much enhanced in the spark spectrum. Table V gives the data on this multiplet. The columns are: the laboratory wave-lengths as measured in the arc by H. Fuchs;⁴ the intensities in arc and spark, as given by Exner and Haschek; the wave-lengths in the sun, from the *Mount Wilson Revi-*

¹ *Tables of Wave-Lengths of Enhanced Lines, Solar Physics Committee*, 1906.

² *Philosophical Transactions of the Royal Society of London*, A, **223**, 161, 1922.

³ *Lick Observatory Bulletin*, No. 332, 100, 1921.

⁴ *Zeitschrift für Wissenschaftliche Photographie*, **14**, 239 and 263, 1915.

sion; the intensities in the sun on Rowland's scale; the wave-lengths in α Cygni according to Wright (reduced to I.A.); Wright's intensities estimated on an arbitrary scale of 1-5; and the excitation potentials.

The ionization potential of Fe I is 7.83, of Ti I is 6.80, and of Mn I is 7.40 volts. The second ionization potentials of these elements are: 16.5 volts (Fe II), 13.60 volts (Ti II), and 15.70 volts (Mn II). From the strength of the multiplet in the sun and in α Cygni, and also from analogy to Fe II and Ti II, it would be expected that Mn II would have its maximum at F0-F8. Unfortunately, very few stars have had their spectra studied so far in the ultra-violet, and no maximum of Mn II can be determined. It seems almost impossible, however, that the manganese lines in α Andromedae can belong to the first stage of ionization. The maximum of the lines in α Andromedae is very sharp, and occurs at a temperature of about 12,500°. The Ti II lines have almost if not entirely disappeared, and only the strongest half-dozen lines of Fe II are still present. Since there can be no doubt that the lines are due to manganese in some stage of ionization, it seems almost certain that this stage is the second (Mn III). This conclusion is in accordance with the behavior of the lines in the laboratory. They are absent in the arc, and are still comparatively weak lines in the spark, unless the excitation is very high. The strength in most of the stars of the helium lines 4026 and 4472, and of the C II line, 4267, shows that the effective excitation must be decidedly higher than in the normal A0 star. If this interpretation is correct, it would follow that the third ionization potential of manganese, not so far determined from spectroscopic analysis, is rather low, hardly more than 20-25 volts. It would be of interest to determine this quantity spectroscopically.

5. In order to determine more accurately the similarities among the stars found to contain Mn III, the intensities of a number of characteristic lines were estimated on several good plates of each star. The number of plates on which the estimates were made averaged about three per star. There were at least two plates in every case. The estimates were made on an arbitrary scale of 1-10. A line of intensity 1 was doubtfully present, while the strongest lines in A stars with the exception of the hydrogen lines were classed as of

intensity 10. Plates of a few of the brighter stars had been recently obtained here on the fine-grain Eastman Process emulsion on which the faint lines appear appreciably stronger than on ordinary fast plates. The material was made homogeneous by applying a systematic correction to the estimates made on the Process plates. This correction was determined by comparing estimates made on process and rapid plates of α Andromedae. The lines whose intensities were estimated were: (1) the strongest Mn III lines in α Andromedae; (2) the He I lines 4026 and 4472; (3) the Si II lines 4128 and

TABLE VI
 Mn III STARS IN ORDER OF RATIO $\frac{4481}{4472}$

Star	H.D.	$\frac{4481}{4472}$	4026	4077	4128	4130	4137	4206	4215	4233	4267
53 Tau.....	B8	.....	.....	.....	6.0	4.7	4.3	5.3	.....	3.0	.....
θ Aur.....	A0	.....	.....	2	7.8	7.8	1.8	3.0	2.5	6.0	.....
ν Her.....	B9	7.8	2.3	3.3	5.7	5.3	2	4.3	3.0	3.7	.....
59 $^{\circ}$ 146.....	B9	5.0	1.3	.....	3.7	4.3	2.6	3.3	.....	2.0	1.0
μ Lep.....	A0	4.3	3.3	3.7	7.0	7.0	4.8	4.8	3.7	5.0	4.0
14 Hya.....	B9	3.8	3.5	1:	6.0	5.5	5.0	4.0	1:	1.5	.....
π Boo.....	A0	3.5	3.7	4.0	6.7	6.0	6.0	5.0	3.3	4.0	3.3
φ Her.....	B9	2.8	3.5	1	6.8	6.3	5.0	2.0	2.0	6.3	1:
α And.....	A0	2.5	4.0	.....	5.6	4.8	4.3	5.0	.....	3.0	3.6
κ Cnc.....	B8	2.1	3.7	.....	6.7	6.0	5.0	4.0	2	4.0	3.3
γ CMa.....	B5	1.7	5.5	.....	5.5	5.0	3.0	3.5	1:	3.5	1.5
33 $^{\circ}$ 3154.....	B8	1.5	3.3	.....	5.3	5.3	5.3	4.0	1:	1.0	.....
β Tau.....	B8	1.5	5.0	.....	4.8	4.8	1.8	1.4	.....	3.2	3.8
α Scl.....	B5	1.1	4.0	.....	4.0	4.0	2.5	.....	.....	1:	5.5

4131; (4) the Sr II lines 4077 and 4215; (5) the lines Fe II 4233, C II 4267, and Mg II 4481. The ratio of the intensities of Mg II 4481 He I 4472 was used to arrange the stars in order of effective excitation. The first two stars, θ Aurigae and 53 Tauri, do not show the helium lines, but they would be classed as A0 on the basis of the intensities of the metallic lines. Table VI gives the estimated intensities. The columns are: the name of the star; the H.D. spectral classification; the ratio 4481/4472; and the estimated intensities of the characteristic spectral lines.

The *Henry Draper Catalogue* classes 53 Tauri as B8, although the helium lines seem to be absent. It is probable that the hydrogen lines and K were used in the classification. The star was announced as a spectroscopic binary by the Lick Observatory and spectral type

revised to A5. The spectrum is rather peculiar in that the strongest lines of Ti II are as strong or stronger than Fe II. Because of the great strength of Mg II 4481 it does not seem possible to classify the spectrum later than A0.

The *Henry Draper Catalogue* classifies θ Aurigae as peculiar, with the following remarks: "The lines 4128.1 and 4131.1 are very strong. The line K is very faint." The spectrum is more completely described in *Harvard Annals*, 28: "This star closely resembles 12 Canum Venaticorum. . . . It differs from that star only in the altered intensity of several faint lines, and the presence of several others not seen in 12 Canum Venaticorum." Although the lines which make the spectrum distinctive are not the same as those in α Andromedae, the stronger Mn III lines are certainly present.

The star 59°146 Cassiopeiae is β 1099. The component stars are 6^m.1 and 6^m.8 and are separated by a distance of 0".2. They are in rapid angular motion. This probably explains why all of the lines are systematically fainter than in the other stars.

Harvard Annals, 28, describes μ Leporis as follows: "This star resembles 21 α Andromedae, so far as can be ascertained from plates taken with two prisms." The Mn III lines are more strongly marked in this star than in any of the others. In spite of the fact that the quality of the lines was estimated as "Many, fair" by the Yerkes observers, they are extremely narrow and deep. The Sr II lines, 4077 and 4215, are well marked.

The star 26 π Bootis is Σ 1864. The magnitudes of the components are 4.9 and 6.0, and their distance is 5"8. There is a very slow progressive change in position angle. The brighter star is the one which contains the Mn III lines. The Sr II lines are also well marked in this star.

The star φ Herculis is noted by Miss Williams¹ as having a spectrum similar to α Andromedae in the strength of the helium lines and of K. She states, however, that the manganese lines were not seen in this star. The stronger Mn III lines are clearly visible on all of the Yerkes plates of good quality. The spectral lines are similar to 5 μ Leporis in their narrowness and depth.

Miss Williams reclassifies the spectrum of α Andromedae as B8.6. Miss Payne² states that the enhanced lines of manganese are

¹ *Harvard Circular*, No. 348.

² *Stellar Atmosphere*, p. 172.

broadly winged. All of the lines are slightly broadened, probably due to rotation, but the manganese lines do not seem to differ in appearance from the other lines of the same intensity in the spectrum. The star α Andromedae is a spectroscopic binary having a period of 96.7 days. Only one spectrum is visible.

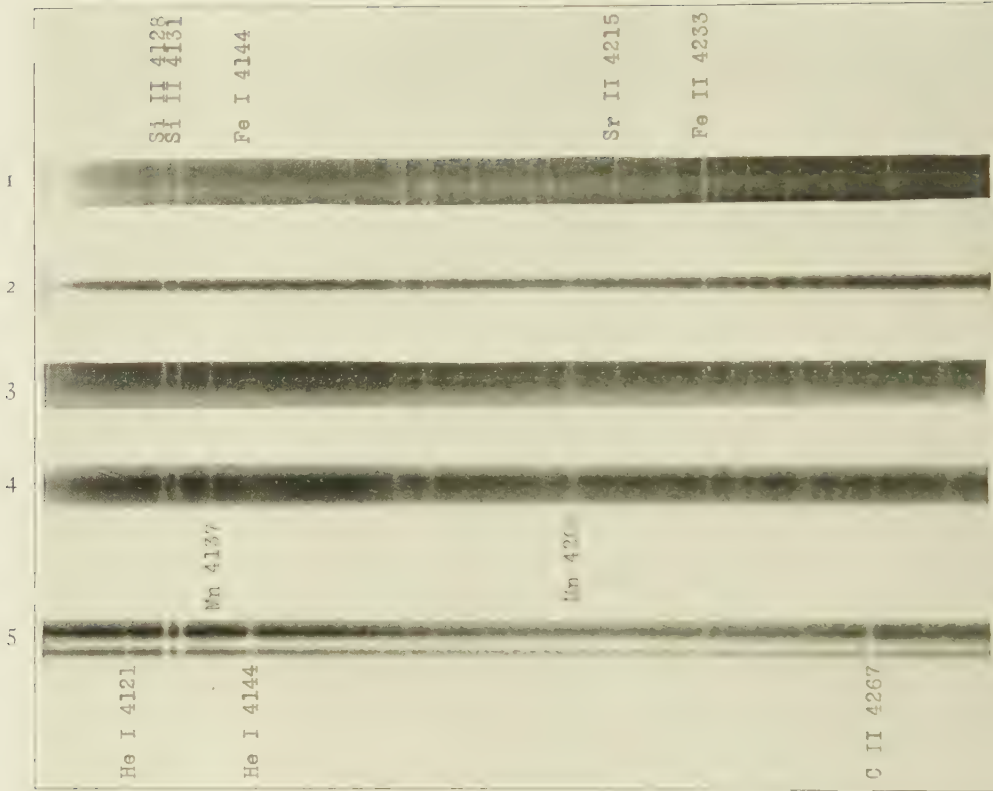
The variability in radial velocity of $76\ \kappa$ Cancri was announced by Frost and Adams in 1904. The lines were reported to be double. All of the principal $Mn\ III$ lines are well marked in this star, including the one situated at 4479, just to the violet of $Mg\ II\ 4481$. The line at 4479 was measured on several plates by Frost and Adams as the component of 4481 in the second spectrum. I have re-examined the plates on which the double lines were measured. There are no other clearly marked duplicities among the other lines, and there seems to be some doubt as to whether the spectra of both components are visible. The spectrographic orbit has been computed by H. Ichinohe using measures of the stronger component exclusively.

The star $+31^{\circ}3154$ Lyrae is $\Sigma\ 2349$. As the magnitude of the fainter component is 10.7 and as the system is probably only an optical one, the companion can have no appreciable effect on the spectrum of the brighter star.

Although, as a rule, the $Mn\ III$ lines are present when the $Si\ II$ doublet 4128 and 4131 is strong and when the helium lines 4026 and 4472 are faint but certainly visible, there are a few stars fulfilling the foregoing conditions which do not seem to contain manganese. It is well known, however, that the stars cannot be arranged in a one-dimensional sequence, and when the general faintness of the $Mn\ III$ lines is considered it seems safe to assume that the appearance of doubly ionized manganese in a normal star of class B0 having lines of good quality is a more or less common phenomenon.

The parallaxes of all the manganese stars, with the exception of α Sculptoris, are included in Schlesinger's recently published *Catalogue of Bright Stars*. The parallaxes have been taken from all sources, and, as the probable errors are not given, the order of accuracy of the deduced absolute magnitudes is somewhat uncertain. Table VII gives the name of the star, the visual magnitude, the parallax from Schlesinger's *Catalogue*, and the absolute magnitude computed from the parallax.

PLATE I



EXAMPLES OF STELLAR SPECTRA

(1) Sirius; (2) φ Herculis; (3) μ Leporis; (4) α Andromedae; (5) β Orionis. The spectra of φ Herculis, μ Leporis, and α Andromedae show the two strongest lines of ionized manganese. Sirius (A α) and β Orionis (B8), in which ionized manganese is absent, are shown to make clear the narrow limits within which the lines occur.

The mean absolute magnitude of the thirteen stars is $+0.01$. This is in almost exact agreement with the mean absolute magnitude of stars of spectral class A0, which is, according to Russell, 0^M_0 . The manganese stars thus seem to be perfectly normal with respect to their absolute magnitudes.

It seems, therefore, safe to conclude (1) that the stage of ionization of the manganese lines in α Andromedae and in the thirteen other stars is the second ($Mn\ III$); (2) that the occurrence of man-

TABLE VII
ABSOLUTE MAGNITUDES

Star	m_v	Par.	M
α And.....	2.2	$0''.040$	$+0.2$
$+59^\circ 146$	5.5	8	.0
53 Tau.....	5.4	10	$+$.4
μ Lep.....	3.3	30	$-$.7
β Tau.....	1.8	35	$+$.5
θ Aur.....	2.7	32	$+$.2
γ CMa.....	4.1	12	$-$.5
14 Hya.....	5.2	9	.0
κ Cnc.....	5.1	8	$-$.4
π Boo.....	4.9	16	$+$.9
ν Her.....	4.6	11	$-$.2
φ Her.....	4.2	15	$+$.1
$+33^\circ 3154$	5.6	7	-0.3

gane lines is a normal feature of many stellar spectra of types B8 - A0; (3) that the maximum of $Mn\ III$ at B9 is in fair agreement with the maxima of other elements having approximately the same ionization potential; (4) that the stars containing $Mn\ III$ are not unusual with regard to their absolute magnitudes.

Plate I shows spectra of three of the manganese stars, with Sirius and Rigel added for comparison.

I wish to express my thanks to Professor Struve for suggesting the problem and for advice and suggestions while the work was in progress. I wish also to thank Professor Frost for the use of the great collection of Yerkes spectrograms and for the opportunity of obtaining additional plates with the 40-inch telescope.

WILLIAMS BAY, WIS.

December 5, 1930

STUDIES IN PECULIAR STELLAR SPECTRA

II. THE SPECTRUM OF B.D.-18° 3789

By W. W. MORGAN

ABSTRACT

The spectrum of the star B.D.-18° 3789 has been found to contain two groups of lines which periodically vary in intensity. The observations are satisfied by a period of 3^d18. The chromium lines in the spectrum form one group, while four europium lines and an unidentified line at λ 4296 make up the other. The two groups seem always to be opposite in phase with respect to each other. Wave-lengths and identifications are given for the spectral lines. Similarities in the appearance and behavior of the spectrum to that of α^2 Canum Venaticorum are pointed out.

1. Variations in the relative intensities of groups of absorption lines in the spectra of variable stars are rather common phenomena, and can be explained generally as an effect of a change in temperature or pressure, or both. When, however, changes are observed in the case of a star whose light is sensibly constant, the difficulties of finding a satisfactory explanation are greatly increased. The problem becomes even more difficult when the lines of one or two elements are observed to change, while other elements having similar properties remain constant.

Probably the most remarkable examples of variations of this kind are shown by certain groups of lines in the spectra of 12 α^2 Canum Venaticorum and 17 Leporis. There are a number of lines in the spectrum of α^2 Canum Venaticorum which were found by H. Ludendorff¹ to vary in intensity. A. Belopolsky² divided the lines into two groups which varied in a period of 5.5 days. One of these groups was identified by F. E. Baxandall³ as being due to the rare earth europium, while C. C. Kiess⁴ has provisionally identified the other with terbium. O. Struve⁵ has found that a large number of the metallic lines in the spectrum of 17 Leporis undergo remarkable changes, both in intensity and in appearance.

¹ *Astronomische Nachrichten*, **173**, 1, 1906.

² *Ibid.*, **196**, 1913, and *Bulletin de l'Académie Impériale des Sciences de St. Pétersbourg* (6th ser.), **7**, 689, 1913.

³ *Observatory*, **36**, 440, 1913, and *Monthly Notices*, **74**, 32, 1913.

⁴ *Publications of the Detroit Observatory, University of Michigan*, **3**, 106, 1923.

⁵ *Astrophysical Journal*, **72**, 343, 1930.

2. I have recently found another star which seems to belong to this rare and interesting class. The star B.D.-18°3789 (vis. mag. 5.74) is classed as of spectral type Aop by the *Henry Draper Catalogue*. The reason for the designation of "peculiar" was stated to be because of the strength of the *Si* II doublet, λ 4128 and λ 4131.

The remarkable changes that take place in its spectrum were first observed on three spectrograms of the star which had been taken with the Bruce spectrograph in 1928. On the first of these plates, taken on March 4, 1928, the europium lines which help to make the spectrum of α^2 Canum Venaticorum so unusual are present, and the strongest, at λ 4205, is one of the most conspicuous lines in the whole spectrum. On the second plate, taken on the following night, March 5, the spectrum has about the same appearance, but on March 18, when the third plate was obtained, the entire character of the spectrum had changed in many respects. The strongest of the europium lines, which fourteen days before had been stronger than any other line in the spectrum with the exception of the hydrogen series, had faded until it was no stronger than a number of other lines in its vicinity. The other three europium lines which had been well marked on March 4 and 5 had become very faint. But the most remarkable change was the appearance of a number of lines which were either entirely absent on the earlier plates, or, in a few cases, at the limit of visibility. It was found that the lines of this second group are due to the element chromium. With a few exceptions, the lines due to other elements seem to be constant in intensity. There is a line at λ 4296.61 which seems to vary in phase with the europium lines. The position agrees well with the *Fe* II line at λ 4296.56, but as the other iron lines in the spectrum seem to be of constant intensity, the identification with iron seems highly improbable.

3. The star was again put on the spectrographic program in January, 1931, and twelve additional one-prism plates were obtained. The variations which had been observed on the early plates were confirmed, and were found to take place in a period of a few days at most. Because of the faintness of the star and its low southern declination, it is difficult to obtain sufficiently exposed plates. It is also almost impossible to obtain more than one plate on one night. For this reason the period cannot be determined with certainty, since

periods of about 1 day cannot be excluded. The variations in intensity of the lines are, however, satisfied by a period of 3.18 days. Figure 1 shows the variation of *Cr* II 4558 and *Eu* II 4205. The phases are computed from the arbitrary epoch 1931, January 0.0. The elements of variation of *Cr* II 4558 are:

$$\text{Max} = \text{J.D. } 2426343.15 + 3^d 18E \text{ (counted from noon) }.$$

Table I gives the estimates of the intensities of the principal variable lines in the observable part of the spectrum. These estimates

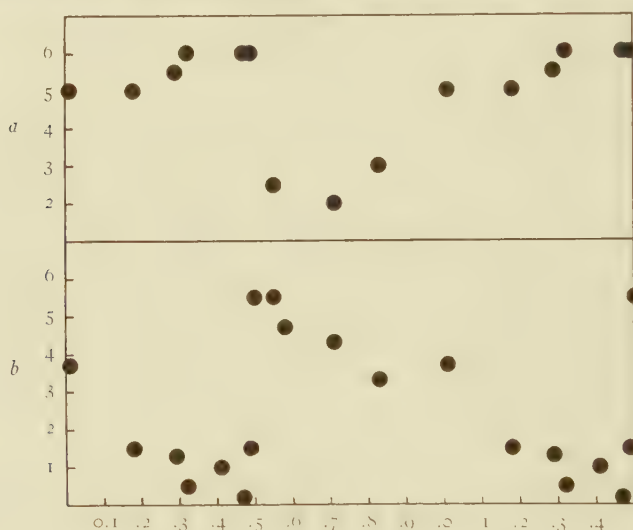
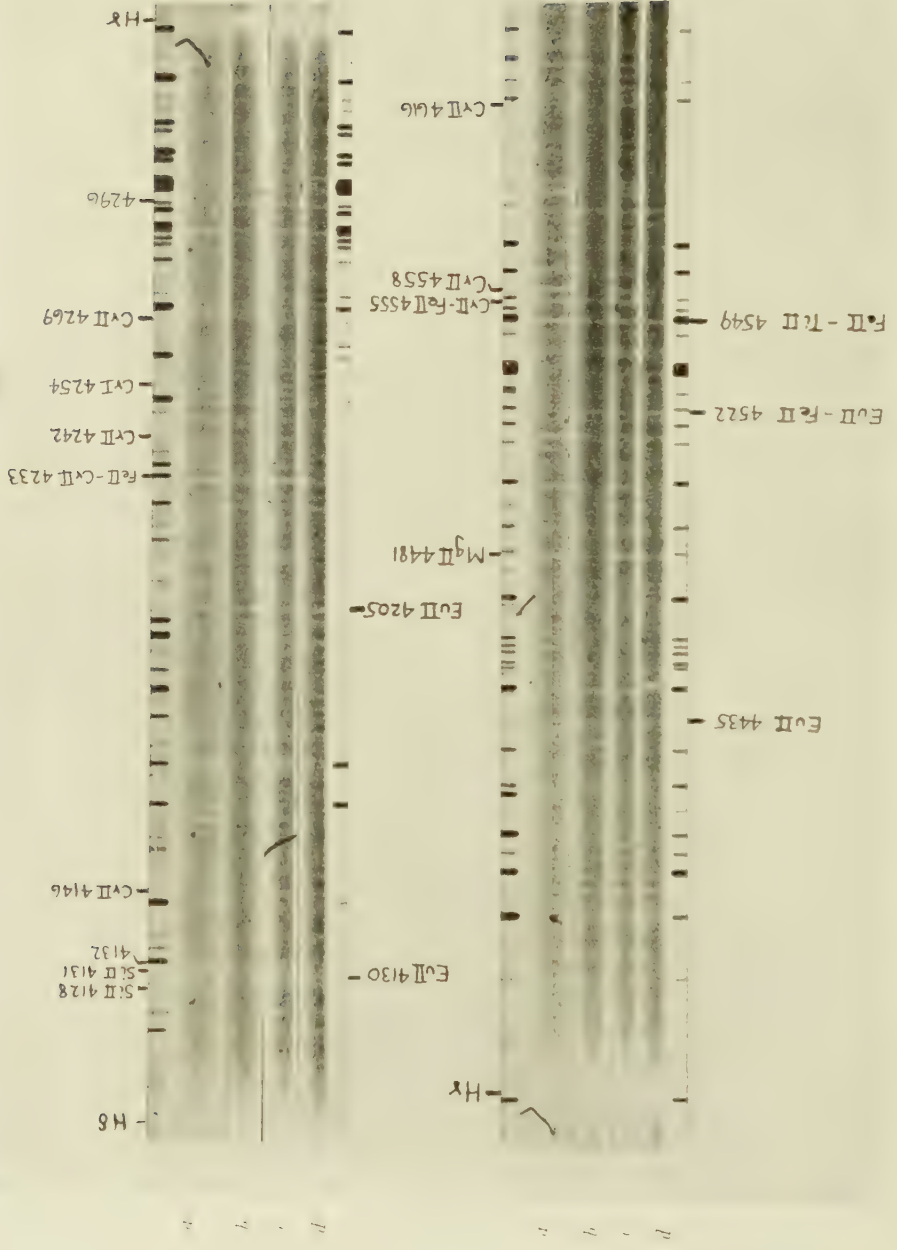


FIG. 1.—Probable curves of variation of: (a) *Eu* II 4205; (b) *Cr* II 4558. Abscissae are tenths of the probable period of 3^d 18; ordinates are visual estimates of intensity.

are, as far as the upper limit of the scale is concerned, independent of the quality of the plates, as the line *Fe* II *Ti* II 4549 has been taken as the standard for intensity 5. The lower limit of the scale is, of course, more uncertain, because of the varying quality of the plates. Only the 1931 plates have been included in Table I.

4. The range in variation of the strongest chromium lines is greater than that of the europium lines. The ultimate *Cr* I line at λ 4254 ranges between complete invisibility and an intensity of 4, and the strongest of the *Cr* II lines at $\lambda\lambda$ 4242, 4269, and 4558, vary

PLATE II



SPECTROGRAMS OF B.D. - 18° 37' 89

a) 1931 Jan 14.475 (U.T.)

b) 1931 Jan 17.470 (U.T.)

from almost complete invisibility to intensities of from 4 to 5. Plate II shows the spectrum of B.D.-18°3789. Two spectrograms are reproduced at maximum and two at minimum phases. The spectra extend from about λ 4100 to λ 4650. The principal lines of chromium and europium are marked, and a few other conspicuous lines are identified. The chromium lines will be found to be stronger on the first and third reproductions than on the second and fourth. Probably the most striking illustration of the variation can be gotten by

TABLE I
ESTIMATES OF INTENSITIES

Date U.T.	Phase	<i>Eu</i> Π 4205	<i>Cr</i> Π 4242	<i>Cr</i> <i>I</i> 4254	<i>Cr</i> Π 4269	? 4296	<i>Eu</i> Π 4435	<i>Mg</i> Π 4481	<i>Eu</i> Π - <i>Fe</i> Π 4518	<i>Cr</i> Π 4558
1931 Jan. 14.475...	0.552	2-3	3-4	3-4	3-4	1	2	6	2-3	5.5
Jan. 16.477...	.182	5	0	0	0	5	3	5	3	1.5
Jan. 17.470...	.494	6	1?	0?	0	5	2-3	3	4	1.5
Jan. 25.476...	.011	5	0?	0?	0?	5	3	3	3	3.7
Jan. 26.453...	.319	6	2	0	0	5	2-3	4	4	0.5
Jan. 30.459...	.578	.....	.....	.....	.....	2	3	4	3	4.7
Feb. 3.435...	.829	3	3	2	2	3	1	5	2-3	3.3
Feb. 5.469...	.468	6	0	0	0	5	3	1-2	4	0.2
Feb. 8.477...	.414	.....	.....	.....	.....	.....	.....	5	2-3	1
Feb. 9.426...	.713	2	2-3	3-4	1?	1:	1	6	2	4.3
Feb. 14.431...	.287	5-6	.....	.....	.....	4	2	2-3	3-4	1.3
Feb. 21.476...	0.502	.....	.....	.....	.....	.....	.....	6	1?	5.5

The phases are expressed in decimal fractions of the period. Complete absence of a line is denoted by intensity zero.

comparing the *Fe* Π -*Ti* Π line at λ 4549 with the two chromium lines at λ 4555 and λ 4558. The europium lines vary in the opposite sense. The most marked variation among the europium lines is shown by λ 4205, which is stronger on the second and fourth spectrograms. Only a few of the variable lines have been marked. It is possible that the hydrogen lines and *Mg* Π 4481 also vary. Over thirty *Cr* Π lines were measured, including a number predicted by T. Dunham and Miss Charlotte E. Moore¹ from a study of incomplete multiplets and found by them in α Persei and in the sun. Owing to the fact that B.D.-18°3789 is at a higher temperature than α Persei, many of the arc lines which cause blends with chromium in the cooler star have disappeared, and most of the *Cr* Π lines are practically un-

¹ *Ibid.*, 68, 37, 1928.

blended. The star is therefore well suited to the study of the relative intensities of the chromium lines which have not been observed in the laboratory.

Table II lists the *Cr* II lines observed in the star between the limits $\lambda\lambda$ 4030-4635. The columns give: (1) the laboratory wave-lengths for all lines observed in the laboratory and the computed wave-lengths for the lines predicted by Dunham and Miss Moore; (2) the intensities in arc and spark, according to Exner and Haschek; (3) the multiplet number of the lines. The multiplets have been consecutively numbered, from lower to higher wave-length. The final columns in the table give: (4) the wave-lengths in B.D.-18°3789; (5) the maximum and minimum intensities in the star; and (6) notes as to blends, etc.

Dunham states¹ that the strongest lines of neutral and singly ionized chromium are of about equal intensity in α Persei. As the strongest *Cr* I line, located at λ 4254, is approximately equal to the strongest enhanced lines in B.D.-18°3789, we would expect the spectral type of the two stars to be about the same, but in other respects they are quite different.

5. The lines in the spectrum of europium have recently been classified according to temperature by A. S. King,² who finds four lines within my observed range which are so strong in the arc that they dominate the spectrum. They are probably lines of low energy-level in the spectrum of *Eu* II, and are strongly reversed in the arc. Table IV gives the wave-lengths of these lines, their intensities in the electric furnace and the arc, the wave-lengths measured in the star, and the estimated intensities of the lines at their greatest and least strength in the star. The estimates are on the same scale as in the preceding tables.

The line at λ 4129.78 is situated between the two *Si* II lines at λ 4128 and λ 4131. It is probably entirely unblended. It seems likely that this line, together with λ 4132, causes the star to seem to have strong *Si* II lines on objective-prism plates. The silicon doublet itself is of only moderate intensity, and seems hardly strong enough to designate the spectrum as "peculiar." In the cooler stars there is a

¹ *Contributions from the Princeton University Observatory*, No. 9, 7, 1929.

² *Astrophysical Journal*, 72, 221, 1930.

TABLE II
LINES OF *Cr* II

λ	Int.	Mult	λ Star	Max. Int.	Min. Int.	Notes
4030.37....	Pred.	1	4030.48	3:	0	
4053.44....	Pred.	2	.....	.....	.....	
4054.10....	Pred.	2	4054.05	3-4	1	
4064.05....	Pred.	1	4064.00	3-4	0?	Blended with <i>Fe</i> I 4063.61; <i>Cr</i> II probably disappears at minimum
4070.94....	0-4	.....	4070.84	.....	.....	
4072.63....	Pred.	3	4072.74	2	0	
4075.66....	Pred.	2	4075.73	2	1	
4076.87....	Pred.	2	4076.93	3	0	
4077.55....	Pred.	2	4077.61	4	1-2	<i>Sr</i> II and <i>Cr</i> II contribute about equally at maximum
4087.63....	Pred.	2	4087.47	1	0	
4088.85....	Pred.	2	.....	.....	.....	
4111.09....	0-4	.....	4110.98	3	0	
4112.57....	Pred.	4	.....	.....	.....	
4145.78....	0-6	}	4146.00	4	0	Enhanced line listed by Lockyer
4146.45....	Pred.		.....	.....	.....	
4170.64....	Pred.		4170.79	2	1	
4171.92....	Pred.	4	4171.95	3-4	1	
4172.62....	Pred.	4	.....	.....	.....	
4179.41....	0-3	3	4179.22	4	0?	
4207.34....	Pred.	3	4207.45	1	1	Line may not be due to <i>Cr</i> II
4215.78....	Pred.	4	4215.60	3-4	1-2	<i>Sr</i> II and <i>Cr</i> II contribute about equally at maximum
4217.08....	Pred.	4	4217.38	3	3	<i>Cr</i> II probably contributes little, if at all, to the star line. In Lockyer's list of enhanced lines; not mentioned by Dun- ham
4224.86....	0-2	.....	4224.58	3-4	1	
4229.82....	Pred.	3	4229.77	2	2	The contribution of <i>Cr</i> II is prob- ably negligible
4233.28....	Pred.	5	4233.25	8	5	<i>Cr</i> II and <i>Fe</i> II about equal in in- tensity at maximum
4242.37....	1-5	5	4242.48	3-4	1	
4252.65....	0-1	5	4252.61	3	0	
4261.81....	0-2	{ 6 5	4261.94	3	2-3	{Line apparently not variable Probably a blend
4261.90....			.....	.....	.....	
4269.30....	0-1	5	4269.11	3-4	0	
4275.58....	0-1	5	4275.32	3	1-2	
4279.00....	Pred.	6	.....	.....	.....	
4280.34....	Pred.	6	4280.83	1-2	2-3	Line probably not due to <i>Cr</i> II
4284.20....	0-2	5	4284.20	2	0	
4504.56....	Pred.	7	.....	.....	.....	
4507.22....	Pred.	7	(4507.74)	1	1:	Blended with <i>Fe</i> II 4508.29
4542.82....	Pred.	7	.....	.....	.....	
4544.69....	Pred.	7	.....	.....	.....	
4555.09....	1-3	8	4555.21	4n	2	Blended with <i>Fe</i> II 4555.89
4558.66....	1-20	8	4558.71	5-6	1:	
4558.84....	Pred.	8	.....	.....	.....	

TABLE II—Continued

λ	Int.	Mult	λ Star	Max. Int.	Min. Int.	Notes
4571.30....	Pred.	7	4572.20	2	2	Line probably entirely due to <i>Ti</i> II 4571.98
4572.83....	Pred.	7				
4588.21....	I-15	8	4588.10	2-3	I	
4588.40....	Pred.	7				
4589.89....	Pred.	8	4590.07	2	I:	
4592.06....	0-2	8	4592.07	2	I:	
4616.72....	0-3-4	8	4616.37	3	I:	
4618.82....	0-8	8	4619.00	2	0	
4621.51....	Pred.	9				
4634.12....	0-8	8	4634.18	2n	0	

TABLE III
LINES OF *Cr* I

λ	Int.	Mult	λ Star	Max. Int.	Min. Int.	Notes
4254.348...	50R-50	1	4254.39	3-4	0	Partially masked by 4275.32? Blended with <i>Ti</i> II 4290.23
4274.868...	50R-30	1	.....	1-2?	0	
4289.731...	30R-30	1	4289.89	4	3-4	

TABLE IV
LINES OF EUROPIUM

λ (KING)	INT.		λ (STAR)	INT.	
	Fur.	Arc		Max.	Min.
4129.639.....	4?	25?	4129.78	2-3	2:
4129.734.....	80	500R			
4204.909.....	5?	30?			
4205.046.....	100	600R	4205.04	7	3-4
4435.473.....	10	20?			
4435.602.....	80	400R	4435.49	3-4	1:
4522.602.....	50	200R	4522.56	4-5	2-3

rather strong line of ionized yttrium at λ 4204.69, but apart from the disagreement in wave-length with the *Eu* II line at λ 4205.05, the star does not seem to contain any yttrium lines. There is also a line due to *V* II at λ 4205.09, but, as stronger lines due to the same element seem to be absent, it can make no sensible contribution to the intensity of the well-marked star line. There is a strong neutral cal-

cium doublet at the position of *Eu* II 4435, but as the ultimate line of *Ca* I at λ 4226 is either absent or very weak in the star, it does not seem that calcium can sensibly disturb the europium line. *Eu* II 4522.56 is blended with the *Fe* II line at λ 4522.64. The two elements probably contribute about equally to the intensity of the stellar line.

6. The principal lines in the spectrum, with the exception of the hydrogen series, were measured for wave-length. The measures were made when the chromium lines were strong. Table V gives the wave-lengths and identifications for the strongest star lines between the limits λ 4030 and λ 4634. The columns give: (1) the measured wave-length; (2) the intensity of the stellar line; (3) the identification and wave-length of the line in the laboratory. In the cases of serious blends the method of Dunham has been used to show the approximate share of the different elements in the blend. Thus, if two elements contribute equally, each is preceded by one plus sign (+). If one contributes twice as much as the other, it is preceded by two plus signs (++), while the other is preceded by one plus sign (+). The approximate share of the different elements in the case of blends was determined from the intensities of unblended members of the same multiplets to which the elements involved belong. A few notes on peculiarities of individual lines are placed at the end of the table.

7. The plates were all measured for radial velocity. The results are shown in Table VI. The columns give (1) the date on which the plate was obtained; (2) the radial velocity; (3) the quality of the plate; and (4) the measurer of the radial velocity.

In spite of the poor quality of most of the plates, the scatter in the measures is larger than it should be, if the velocity is constant. The two best plates of the 1931 series give positive velocities, while the three 1928 plates give negative velocities of from 14 to 23 km. The observations in 1931 were plotted according to the phases computed from the variable chromium line at λ 4558. No certain periodicity was shown. It seems probable that the radial velocity is variable, but a long series of good plates will be necessary to settle the question.

Adams and Joy¹ have published a value of -9.5 ± 1.8 km/sec. for the radial velocity. This value was determined from five plates. The

¹ *Ibid.*, 57, 149, 1923.

mean velocity from the Yerkes measures is -8.2 km sec., in very good agreement with the Mount Wilson value.

TABLE V
WAVE-LENGTHS AND IDENTIFICATION OF LINES

λ	Int.	Identification	λ	Int.	Identification
4046.02	2-3	Fe I 45.82	4289.59	4	Ti II 90.23
4049.07	3	-?Cr I 48.76	4291.25	1	+Fe I .13; ++ +Ti II .10
4054.05	3-4	+Cr II .08; +Ti II 53.84	4296.64	1	Fe II .56
4064.00	4	++ +Cr II .05; +Fe I .60	4299.87	2	Ti II 00.05
4070.81	2:	Cr II .99	4301.99	3	Ti II .93
4072.71	3	Cr II .63	4303.19	3	Fe II .18
4075.73	2	Cr II .66	4307.86	1-2	?Ti II .89
4076.03	3	Cr II .88	4312.87	1-2	Ti II .88
4077.01	4	+Sr II .71; +Cr II .58	4314.96	3	Ti II .98
			4325.35	4	-Fe I .77
4113.26	3-4		4330.36	4	+Ti II .26; +Ti II .71
4110.23	1-2N		4351.82	1	Fe II .77
4122.08	3-4N	-?Fe II .67	4367.97	2-3	Ti II .67
4128.02	3-4	Si II .05	4374.72	2	Sc II .46
4129.01	2	Eu II .73	4383.57	2	Fe I .55
4131.02	1-2	Si II 30.88	4385.17	2-3	Fe II .39
4132.37	4	?O .54; ?Fe I .07	4395.27	2	Ti II .04
4138.10	1-2N		4400.21	2	Ti II 99.77
4143.50	2-3	-?Fe I .88	4404.90	1	Fe I .75
4146.00	4	Cr II 45.78	4410.83	1	Ti II 11.10
4161.10	4	-?Ti II .52 ch	4415.00	1	Fe I .13
4163.85	2-3	Ti II .65 ch	4416.82	2	Fe II .81
4170.79	2	Cr II 64	4435.04	1:	Eu II .60
4171.05	3-4	++ +Cr II .92; +Ti II .90	4444.23	2-3N	?Ti II 43.80
4173.53	2-3:	Fe II .48	4481.34	5	Mg II .25
4179.22	4	++ +Cr II .41; +Fe II .78.87	4480.32	1-2N	Fe II .21
			4501.82	2n	Ti II .27
4181.85	2	?Fe I .77	4507.81	1	+Cr II .22; ++ +Fe II .08.20
4186.02	3	?Fe I 87.05		2	?Cr I .01
4190.28	2	-?Ti II .29	4511.71	3-4	+Fe II .34 +?
4191.37	2	?Fe I .44	4515.39	2	Fe II .24
4195.16	2	?Fe I .34	4520.16	2-3	+Fe II .64; +Eu II .60
4198.13	3	?Fe I .31	4522.00	1-2	Ti II .97
4205.10	3-4	Eu II .05	4533.37	1:	
4207.15	1	Cr II .34	4535.80	2NN	
4215.00	3-4	+Cr II 78; +Sr II .52	4540.57	5	++ +Ti; .64 +Fe .48
4217.38	3	Cr II .08	4545.00	4n	Cr II .05
4224.58	3	?Cr II .86	4549.58	5	++ +Cr II .66; ? +Cr II .84
4227.49	3	-?Fe I .44	4555.24	1	Ti II .77
4229.77	2	Cr II .82	4558.71	1	?Cr I .51
4233.05	7	+Cr II .28; Fe II 16		2-3	-Cr II 71.30; ++ +Ti 71.98; -Cr II 72.83
4242.18	3-4	Cr II .37	4563.03	1-2	Fe II .31
4246.06	3	Sc II .83	4565.00	3NN	+Fe II 2.84; ++ +Fe II 3.84 + r
4250.10	3N	+Fe I .13; ++ +Fe I .79	4572.22	3	++ +Cr II .21; Cr II .41
4252.61	3	Cr II 65		2	+ [Cr II .80; Cr II 95]
4254.39	3-4	Cr I .34	4583.11	2	+Ti II .96
4258.00	3	?Fe II .17		3	Cr II .06
4261.91	3	+Cr II .81; ++ +Cr II 90	4588.00	3	Cr II .72
			4590.07	2	Cr II 18.82
4263.06	3NN			2-3	+?Fe I .05; +?Cr I 26.18
4269.04	3-4	Cr II 30	4592.37	2n	Fe II .33
4271.06	2	Fe I 76	4592.37		Cr II .12
4273.35	2	Fe II .33	4592.37		
4275.32	3	Cr II .58	4601.00		
4278.01	2-3	Fe II .17	4625.85		
4280.53	1	+Cr II .34; ++ +Cr II 81.08	4629.72		
			4634.18		
4284.20	2	Cr II .20			

The line at λ 4113.26 seems to vary in phase with the Cr II lines. Exner and Haschek list a chromium line of intensity 1 in the spark at λ 4113.18. The line at 4444.23 gave discordant velocities on several of the plates. It is possible that it varies in position.

8. If the variation in intensity of the Cr II lines be considered as due to periodic changes in effective excitation in the atmosphere of the star, difficulties immediately arise. On the assumption of changes in excitation, neutral chromium should vary oppositely in phase to ionized chromium, since the increased strength of Cr II would be obtained at the expense of Cr I. (From the general appearance of the spectrum, it would seem that the higher stages of ionization can be

TABLE VI
MEASURES OF RADIAL VELOCITY

Date U.T.	Vel.	Qual.	Meas.
1928 Mar. 4.438....	-20.4	g	σ
	-23.3		M
Mar. 5.342....	-17.9	g	σ
	-17.9		M
Mar. 18.381....	-13.7	g	σ
	-16.0		M
1931 Jan. 14.475....	-15.1	f	M
Jan. 16.477....	-16.2	p	M
Jan. 17.470....	+ 5.1	g	M
Jan. 25.476....	- 9.2	p	M
Jan. 26.453....	+ 2.4	g	M
Jan. 30.459....	- 7.9	vp	M
Feb. 3.435....	- 9.7	p	M
Feb. 5.469....	+ 7.2	f-p	M
Feb. 8.477....	- 3.8	p	M
Feb. 9.426....	- 0.8	f	M
Feb. 14.431....	- 7.0	p	M
Feb. 21.476....	-13.7	p	M

σ = O. Struve; M = W. W. Morgan.

neglected.) The observations, however, show that the line of Cr I at λ 4254 varies in phase with Cr II. The other two members of the ultimate triplet of Cr I do not show much variation, probably because of blends. It thus seems that, as far as can be judged by appearances, the actual number of chromium atoms effective in absorbing the observed lines varies in the period of the variation in intensity. In the case of the europium lines, there is no check on the behavior of the lines of the neutral atom. It is difficult to find any relationship between the elements chromium and europium, but their complementary behavior seems very suggestive.

It also seems remarkable that, in the only other star known to contain strong lines of europium, the same lines form a group which

varies in intensity. In α^2 Canum Venaticorum the europium lines vary from almost complete invisibility to intensities which place them among the strongest lines in that star's spectrum. It is not possible to generalize with only two stars, but it seems possible that europium is connected with some state of physical change. It would be necessary to find more of such stars before an adequate study could be made of the phenomenon. The importance of such a study can hardly be overemphasized, as it seems that in stars of this class we are observing results of changes which may illustrate the basic laws of stellar evolution.

YERKES OBSERVATORY
WILLIAMS BAY, WIS.
February 16, 1931

STUDIES IN PECULIAR STELLAR SPECTRA

III. ON THE OCCURRENCE OF EUROPIUM IN A-TYPE STARS

By W. W. MORGAN

ABSTRACT

Thirteen stars of spectral types A₀–A₃ have been found which show the two strongest lines of *Eu*⁺. Seventeen other stars have a line in their spectra coinciding in position with the strongest *Eu*⁺ line, which cannot be accounted for by any other element. These stars, together with α^2 Canum Venaticorum, seem to make up a group of “europium stars” in the early subdivisions of spectral type A.

1. The first announcement of the detection of the rare earth europium in stellar spectra was made by J. Lunt¹ in 1907. From measures of the radial velocity of α Bootis and β Geminorum he found that the *Ca* I line at λ 4435.690 (I.A.) was shifted 0.049 Å to the violet of its normal position in α Bootis and 0.040 Å in the case of β Geminorum. He found confirmation of the discordant velocity from measures of radial velocity made at the Yerkes and Lowell observatories. Altogether eight stars were listed, of which α Bootis was common to all three sources. On the assumption that an unknown line of equal intensity with *Ca* I 4435.690 was the cause of the discordance, he identified the disturbing line with *Eu* 4435.59. He states that there are strong lines in the spectrum of Arcturus in the positions of the two strongest europium lines at λ 4129 and λ 4205. From an examination of plates of Arcturus I have come to the conclusion that the identification of the disturbing line at λ 4435 with europium is difficult to establish, since the calcium doublet is well marked and both of the stellar lines at λ 4129 and λ 4205 are probably blends in the spectrum of the star.

L. E. Jewell² first suggested the identification of three lines in the flash spectrum with europium from plates taken at the eclipse of the

¹ *Proceedings of the Royal Society of London*, A, **79**, 118, 1907.

² *Publications of the United States Naval Observatory* (2d ser.), **4**, App. I, PD-121, 1905.

sun in 1900. A more complete discussion was made by F. W. Dyson¹ from spectra obtained at the eclipses of 1900, 1901, and 1905. Table I gives his identifications of the europium lines in the flash spectrum with the laboratory wave-lengths and intensities from Exner and Haschek. All of the data are taken from Dyson, and the wave-lengths are expressed in the old Rowland system.

In 1913 F. E. Baxandall² announced the identification with the strongest lines of europium of two of the lines showing the most marked variation in intensity in the spectrum of α^2 Canum Venaticorum. From a comparison with laboratory wave-lengths he identified five other lines with europium by means of measures made by

TABLE I
EUROPIUM IN THE CHROMOSPHERE (DYSON)

CHROMOSPHERE		SUN		LABORATORY		
λ (Row.)	Int.	Int.	IDENTIFICATION	λ (Row.)	Intensity	
					Spark	Arc
3907.28.....	2	.....	<i>Eu</i>	3907.3	30	30
3972.02.....	2	o?	<i>Eu</i>	3972.13	50	50
4129.87.....	4	1	<i>Eu</i>	4129.88	100	100
4205.21.....	6	1	<i>Eu</i>	4205.19	100	50
4435.53.....	2	$\begin{cases} 5 \text{ Ca} \\ 4 \text{ Ca} \end{cases}$	Possibly <i>Eu</i> 4435.7	.....	.....	.....

A. Belopolsky. The intensities of the lines in the laboratory and the wave-lengths in the laboratory and star are given in Table II. The wave-lengths are in the old Rowland system. The lines λ 4129 and λ 4205 had been shown by Belopolsky³ to vary periodically in intensity, in phase, in a period of about 5.5 days. An examination by Baxandall of spectrograms obtained at South Kensington of Sirius, α Cygni, and Procyon presented varying degrees of probability of the occurrence of europium in these stars. His results are given in Table III. The wave-lengths are in the Rowland system.

¹ *Philosophical Transactions of the Royal Society of London*, A, 206, 403, 1906.

² *Observatory*, 36, 440, 1913, and *Monthly Notices of the Royal Astronomical Society*, 74, 32, 1913.

³ *Astronomische Nachrichten*, 196, 1, 1913; also *Bulletin de l'Académie Imp. des Sciences de St. Petersburg* (6th ser.), 7, 689, 1913.

From the foregoing evidence Baxandall concluded that the occurrence of europium in α Canis Majoris was established. He considered the evidence unconvincing in the case of α Cygni, and inconclusive

TABLE II
EUROPIUM IN α^2 CANUM VENATICORUM (BAXANDALL)

λ (ROWLAND)	LABORATORY (E. AND H.)			Remarks
	Intensity		α^2 CVn (Belopolsky) λ (Rowland)	
	Spark	Arc		
3930.65.....	50	50	3930.67	Masked by <i>He</i> in star
3972.16.....	50	50	.....	
4129.90.....	100	100	4130.04	
4205.20.....	50	100	4205.20	Stellar line partly due to <i>Ca</i> 4435.85 Stellar line probably chiefly due to <i>pFe</i> line 4522.80
4435.75.....	30	50	4435.77	
4522.76.....	15	20	4522.87	
4594.22.....	10	100	4594.26	

TABLE III
EVIDENCE FOR OCCURRENCE OF EUROPIUM IN A AND F STARS (BAXANDALL)

LABORATORY (E. — H.)	α CMA		α CYG		α CMR	
λ (Rowland)	λ (Rowland)	Notes	λ (Rowland)	Notes	λ (Rowland)	Notes
3930.65.....	3930.52	Probably blend of $Eu-Fe$	3930.52	Possibly blend of $Eu-Fe$	.....	Masked by Ca K
3972.16.....	.....	Masked by $H\epsilon$	.....	No evidence for stellar line	.....	Masked by Ca H and $H\epsilon$
4129.90.....	4129.91	Faint, probably Eu only	.....	No evidence for stellar line	4129.6	Weak stellar line apparently more refrangible than Eu line
4205.20.....	4205.21	Faint, probably Eu only	4205.2	Possibly blend of $Eu-pV$	4205.10	Possibly Eu only
4435.70.....	.....	Doubtful in stellar spectrum	.....	No evidence for stellar line	4435.9	Probably chiefly Ca ; possibly Eu also
4522.70.....	4522.7	Chiefly pFe 4522.80, but possibly a blend with Eu	4522.7	Strong stellar line, chiefly pFe ; possibly blend of $Eu-pFe$	4522.9	Probably chiefly pFe ; possibly Eu also
4594.22.....	4594.18	Stellar line probably Eu	4594.42	Possibly Eu	4594.3	Possibly Eu only; evidence for V 4594.27 weak

for α Canis Minoris. He also compared the strongest europium lines with the solar spectrum.

S. A. Mitchell¹ attributed six lines in the flash spectrum as observed at the eclipse of 1905 to europium. In a later paper² a catalogue of lines is given, determined principally from the chromospheric spectra of 1905 and 1925. In this paper four lines are ascribed to Eu^+ . The wave-lengths in the chromosphere together with other data are given in Table IV. The wave-lengths are in Å.

TABLE IV
OCCURRENCE OF Eu^+ IN THE CHROMOSPHERE (MITCHELL)

λ (Å.) CHROMOSPHERE	λ (Å.) SUN	ELEMENT	INTENSITY		HEIGHT IN KM
			Disk	Flash	
3906.99.....	3906.96	Eu^+	1	2	600
3971.89.....	3971.91	Eu^+-Fe	1	3	700
4129.73.....	4129.73	Eu^+	1	10	600
4205.06.....	4205.06	V^+-Eu^+	2	6	600

It seems that the wrong solar line was identified with the europium line at λ 3907. From a more exact determination of the wave-length of the Eu^+ line by A. S. King identification with another solar line is indicated (see Table VII).

In an extension of the work of Ludendorff, of Belopolsky, and of Baxandall on the spectrum of α^2 Canum Venaticorum, C. C. Kiess³ identified several other lines with europium among those found to vary in intensity. Table V gives all of the lines which he considered to be due to europium. The wave-lengths are on the old Rowland system.

Miss Cecilia Payne⁴ suggested the identification of two lines measured by Lockyer and Baxandall in the spectrum of γ Cygni with the two strongest lines of europium. She also identified two weak lines in the solar spectrum as being identical with the same europium lines. As Adams and Joy have pointed out,⁵ however, it seems that

¹ *Astrophysical Journal*, **38**, 407, 1913.

² *Ibid.*, **71**, 1, 1930.

³ *Publications of the Observatory, University of Michigan*, **3**, 106, 1919.

⁴ *Harvard Bulletin*, No. 841, 2, 1926.

⁵ *Proceedings of the National Academy of Sciences*, **13**, 393, 1927.

the wrong lines were identified with europium by Miss Payne in the solar spectrum. Adams and Joy have published wave-lengths determined for the two strongest europium lines from large-scale spectrograms of γ Cygni taken with the coudé spectrograph of the Mount Wilson Observatory. Their measures are included in Table VI. The wave-lengths are expressed in I.A.

TABLE V

EUROPIUM LINES IN α^2 CANUM VENATICORUM (KIESS)

λ (ROWLAND) Star	λ (ROWLAND) Laboratory
3820.0.....	<i>Eu</i> 3819.80
3899.1.....	(<i>Eu</i> 3898.90)
3907.3.....	<i>Eu</i> 3907.29
3930.6.....	<i>Eu</i> 3930.66
3972.0.....	<i>Eu</i> 3972.16
3978.6.....	(<i>Eu</i> 3978.60)
4085.8.....	(<i>Eu</i> 4085.54)
4129.7.....	<i>Eu</i> 4129.90
4205.3.....	<i>Eu</i> 4205.20
4435.4.....	<i>Eu</i> 4435.75
4522.8.....	<i>Eu</i> 4522.76
4912.5.....	<i>Eu</i> 4912.61

TABLE VI

EUROPIUM LINES IN γ CYGNI (ADAMS AND JOY)

λ Lab. (I.A.)	λ Sun (I.A.)	$\lambda \gamma$ Cyg. (I.A.)
4129.72.....	4129.73	4129.72
4205.03.....	$\left\{ \begin{array}{l} 4205.03 \\ 4205.08 \end{array} \right. V^+$	4205.06

D. H. Menzel¹ has called attention to the remarkable behavior of the lines due to the rare earths on a moving plate spectrogram taken at the eclipse of 1905 by W. W. Campbell. Instead of reversing to dark lines at the limb of the sun they remained in emission far in on to the disk of the sun.

The recent determination of accurate wave-lengths of the strongest europium lines and the temperature classification of all the lines, by King,² have made it seem desirable to try to obtain more data as

¹ *Publications of the Astronomical Society of the Pacific*, **39**, 359, 1927.

² *Astrophysical Journal*, **72**, 221, 1930.

to the occurrence and behavior of the element in the stars. Table VII gives the wave-lengths and intensities in the furnace and arc of all of the europium lines having intensities of 30 or greater. The wave-lengths to two places are by Eder;¹ the more accurate ones were measured by King. The lines which occur in the sun are also listed. The wave-lengths, identifications, and intensities in the sun

TABLE VII
INTENSITIES, WAVE-LENGTHS, AND TEMPERATURE CLASSIFICATION OF
STRONGEST EUROPIUM LINES (A. S. KING) WITH
OCCURRENCE IN THE SUN

λ (I.A.)	INTENSITIES		CLASS; NO. COMPS.	λ SUN	IDEN.	INT. DISK	INT. SPOT
	Arc	Fur.					
3884.76....	50	8	III, 3	.....	.....	.....	.....
3907.113....	300R	30	III E, 4	3907.116	.....	oNd?	.....
3917.30....	30	5	III, 3	.....	.....	.....	.....
3930.425....	15?	2?	III E	.....	.....	.....	.....
3930.504....	300R	50	III E, 3	3930.515	Eu ⁺ ?	o	.....
3971.899....	20?	3	III E	.....	.....	.....	.....
3971.989....	400R	60	III E, 3	3971.996	Eu ⁺ ?	od?	o
4039.20....	30	12	III, 2	.....	.....	.....	.....
4129.639....	25?	4?	III E	.....	.....	.....	.....
4129.734....	500R	80	III E, 3	4129.732	Eu ⁺	I	I
4204.909....	30?	5?	III E	(4204.897)	.....	-2	.....
4205.046....	600R	100	III E, 3	4205.029	Eu ⁺ ?	I	2*
4298.73....	30	4?	III	.....	.....	.....	.....
4355.10....	30	.....	V E	.....	.....	.....	.....
4435.473....	20?	10	III E	.....	.....	.....	.....
4435.602....	400R	80	III E, 3	Masked by Ca 4435.690	.....	.....	.....
4522.602....	200R	50	III E, 4	Masked by Fe ⁺ 4522.640	.....	.....	.....
4593.993....	500R	200R	II	.....	.....	.....	.....
4612.7122	300R	150R	II	.....	.....	.....	.....
4661.865....	250R	100R	II	.....	.....	.....	.....

* Blended with V* in spot spectrum.

were taken from the *Mount Wilson Revision of Rowland's Preliminary Table of Wave-Lengths*.

King describes the strongest lines in the spectrum as follows:

The lines of low excitation in the ionized spectrum have intensities seldom found in rare-earth spectra. These are $\lambda\lambda$ 3907.1, 3930.5, 3971.9, 4129.7, 4205.0, 4435.6, 4522.6. The line λ 3819.6, outside the range here studied, belongs to the group. In structure each line consists of an unresolved triplet, with a fourth

¹ *Sitzungsberichte der Akademie der Wissenschaften in Wien*, IIa, 126, 473, 1917.

line, usually separated in the furnace spectrum, on the violet side. . . . The ionized character of these lines was clearly shown by their almost complete extinction when caesium was added in the furnace; but with europium alone the lines are strong in the furnace, and with long exposures show at temperatures as low as 2000°C

The neutral lines of europium present a similar contrast between groups. Three low-temperature lines occur at $\lambda\lambda$ 4593.993, 4627.122, 4661.865. . . .

As the europium lines seemed to reach their greatest intensity in α^2 Canum Venaticorum whose spectral type is Aop, it seemed that a search through the large collection of spectrograms of A-type stars obtained at the Yerkes Observatory might bring to light other "europium stars." The stars examined cover a range of spectrum Ao–A₃ inclusive. The number of stars examined in each spectral subdivision is given in Table VIII. It should be pointed out that the broad, hazy lines in many A-type stars caused by rapid rotation prevent the observation of comparatively weak lines such as the europium ones. For this reason stars whose spectral lines are of poor quality were omitted from the discussion.

TABLE VIII

NUMBER OF A STARS EXAMINED FOR EUROPIUM

Sp.	No. Stars
Ao	200
A ₂	110
A ₃	50

The total number of stars examined on Yerkes spectrograms is therefore 360. Of this number 34 were found whose spectrum contained a line at λ 4205 agreeing in position with the strongest line of Eu^+ . Of these, 13 showed lines at both λ 4129 and λ 4205. The number of stars mentioned includes α^2 Canum Venaticorum, α Canis Majoris, and α Cygni, which had been previously found by Baxandall. One of the stars found, B.D. – 18°3789, proved to have a spectrum of unusual interest and has formed the subject of a separate paper.¹ The four strongest europium lines in its spectrum were found to vary in intensity in a probable period of 3.2 days. The chromium lines in the spectrum are also variable in intensity in the same period, but chromium attains its maximum intensity at the time when the europium lines are at a minimum.

¹ *Astrophysical Journal*, 74, 24, 1931.

Table IX lists the stars found to have lines corresponding in position to one or more of the strongest europium lines.

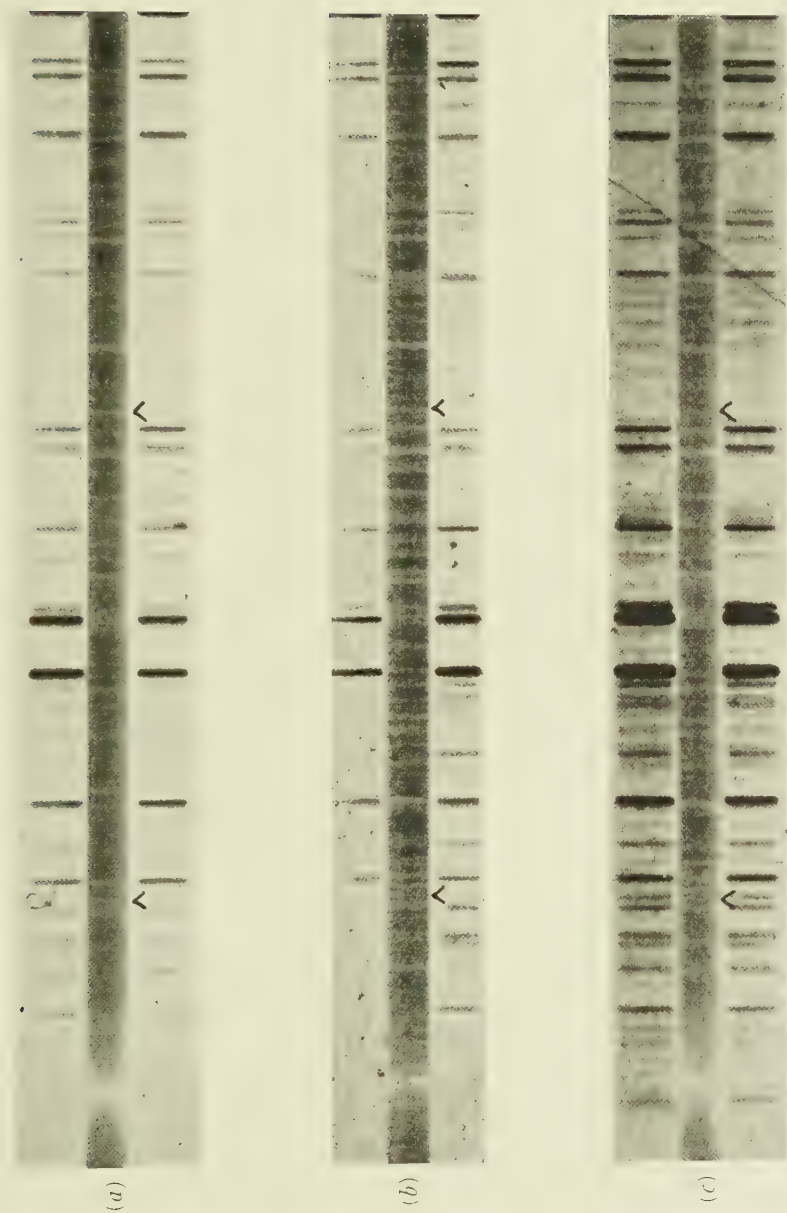
The intensities of a selected group of lines were estimated on two plates for each star. The wave-length of the line at λ 4205 was de-

TABLE IX
A-STARS CONTAINING LINES CORRESPONDING IN POSITION
WITH STRONGEST EUROPIUM LINES

Star	α (1900)	δ (1900)	Vis. Mag.	Spectrum
5 γ Ari (S).....	1 ^h 48 ^m	+18° 48'	4.83	Aop
+70° 257 Cam.....	3 39	+70 34	5.40	Ao
+25° 624 Tau.....	3 44	+25 17	5.38	A3
68 Tau.....	4 20	+17 42	4.24	A2
4 Cam.....	4 40	+56 35	5.35	A2
+11° 646 Ori.....	4 40	+11 31	5.43	Ao
16 Ori.....	5 04	+ 9 42	5.42	A2
14 Aur.....	5 00	+32 34	5.14	A2
27 ϕ Aur.....	5 38	+49 47	5.52	Ao
40 Aur.....	6 00	+38 29	5.31	A3
9 α CMa.....	6 41	-16 35	-1.6	Ao
66 α Gem (ft).....	7 28	+32 06	2.85	Ao
2 UMa.....	8 26	+65 29	5.39	Ao
49 Cnc.....	8 39	+10 27	5.58	Aop
65 α Cnc.....	8 53	+12 15	4.27	A3
67 UMa.....	11 57	+43 36	5.07	A3
17 Com.....	12 24	+26 28	5.38	Aop
77 ϵ UMa.....	12 50	+56 30	1.68	Aop
12 α^2 CVn.....	12 51	+38 51	2.90	Aop
78 Vir.....	13 29	+ 4 10	4.93	A2p
-18° 3789 Vir.....	14 13	-18 15	5.74	Aop
7 μ Lib.....	14 44	-13 44	5.38	A2p
-10° 4135 Lib.....	15 27	-19 20	5.46	A2
+55° 1779 Dra.....	15 45	+55 41	5.79	A2
37 ϵ Ser.....	15 46	+ 4 47	3.75	A2
52 Her.....	16 46	+46 10	4.86	A2p
+25° 3246 Her.....	17 16	+25 38	5.32	A2
6 ζ Lyr (br).....	18 41	+37 30	4.29	A3
10 Aql.....	18 54	+13 46	5.94	A3p
58 π Dra.....	19 20	+65 31	4.63	A2
73 Dra.....	20 33	+74 37	5.18	A2p
50 α Cyg.....	20 38	+44 55	1.33	A2p
+48° 3390 Cyg.....	21 23	+48 24	5.31	A3
32 Aqr.....	22 00	- 1 23	5.23	A3

terminated for all of the stars, and the line at λ 4129 was measured in the thirteen cases where it was found to be present. These results are given in Table X. The columns give: (1) the name of the star and the spectral type; (2) the estimates of intensity of twenty-one lines, including those at the position of the europium lines; and (3)

PLATE III



Spectra of (a) 78 Virginis, (b) 16 Orionis, and (c) 19°4135 Librae in the region $\lambda\lambda$ 4090-4270. The wave-lengths increase toward the right. The He^+ lines at $\lambda\lambda$ 4129 and 4205 are marked.

the measured wave-lengths for λ_{4129} and λ_{4205} , and their deviations from the laboratory positions.

As Yerkes one-prism plates are generally weak to the violet of λ_{4000} , it was thought best to observe lines which are situated to the red of this position. This reduced the number of strong ionized europium lines to four in the observable range. These were $\lambda\lambda_{4129, 4205, 4435}$, and 4522 . Of these, the last two may be seriously blended. There is a strong neutral calcium doublet at λ_{4435} , which is present in the cooler A stars. The line at λ_{4522} is hopelessly blended with the Fe^+ line at the same position. There is a moderately strong V^+ line at $\lambda_{4205.082}$ in the sun. As the strongest Eu^+ line lies at $\lambda_{4205.046}$ the presence or absence of V^+ was determined from other, stronger vanadium lines. Table XI gives the strongest lines of ionized vanadium in the region observed.

TABLE X

	Star	Sp.	V^+ 4023	Si^+ 4128	4130	Si^+ 4131	4132	Fe 4202	4205	Sr^+ 4215	$Ca-Fe$ 4227	Fe^+ 4233
1.....	γ Ari (S)	Aop	o	2-3	o	I	2	I	I-2	I-2	I	3-4
2.....	$70^\circ 257$ Cam	Ao	o	I-2	o	I	I-2	I-2	I-2	4-5	2	3-4
3.....	$25^\circ 624$ Tau	A3	o	I	o	o	I	I	I	I	I	o
4.....	68 Tau	A2	o	2-3	o	I-2	2-3	2	I	2-3	I	3
5.....	4 Cam	A2	o	2	I	o	I	2	2	2-3	2-3	2-3
6.....	$+11^\circ 646$ Ori	Ao	o	2	o	I	I	2-3	I	2-3	3	2-3
7.....	16 Ori	A2	o	3	I	2	3	2-3	2-3	4-5	3	3-4
8.....	14 Aur	A2	o	I-2	o	I	2	2	I	3-4	3-4	3-4
9.....	o Aur	Ao	o	I	o	o	2	I	I	I	I-2	2
10.....	40 Aur	A3	o	2-3	o	I	3	3	3	5	3-4	4
11.....	a CMa	Ao	I	4	I	4	2-3	2-3	I	3-4	2	5
12.....	a Gem (fu)	Ao	I:	2	o	2	2	3	I	3-4	3	3
13.....	2 UMa	Ao	o	2	I	I	2	2	I-2	4-5	2	3
14.....	49 Cnc	Aop	o	3-4	o	3-4	I-2	I?	I-2	2-3	I	2-3
15.....	a Cnc	A3	o	I-2	o	I?	I-2	I-2	I	2-3	2-3	3
16.....	67 UMa	A3	o	I-2	o	o	I	I-2	I	3	2	2
17.....	17 Com	Aop	o	2	o	I	2	I	2	2-3	I	3
18.....	e UMa	Aop	I	3-4	o	2	4	2	2	4	2-3	5-6
19.....	α^2 CVn (max)	Aop	o	4-5	3	4-5	3-4	o	4-5	2	2-3	3
20.....	α^2 CVn (min)	.....	.....	5	o	5-6	I-2	o	I-2	2	I	4-5
21.....	78 Vir	A2p	o	I-2	2	I	3-4	I	2-3	4	I	3-4
22.....	$-18^\circ 3780$ Vir (max)	Aop	o	2	2	I	3	o	4-5	I	2	2
23.....	$-18^\circ 3780$ Vir (min)	.....	.....	2	I	I	3	I	2	3	2	5
24.....	μ Lib	A2p	o	I	I	I	2	I	I	6	I-2	2-3
25.....	$-19^\circ 4135$ Lib	A2	o	3	I-2	2-3	3	3	2	3-4	3-4	3-4
26.....	$55^\circ 1779$ Dra	A2	o	3	o	I	3	3	I-2	3-4	3	3-4
27.....	e Ser	A2	I	3	o	3	3-4	4	I-2	6	4	6
28.....	52 Her	A2p	o	I-2	I	I	2-3	I-2	I-2	4-5	I-2	3
29.....	$25^\circ 3246$ Her	A2	I	2	o	I-2	I	2	I	4	2-3	4
30.....	ξ Lyr (br)	A3	2	3	I	2	3	3	3	4-5	4	4
31.....	10 Aql	A3p	o	2	2	I	2	2	I-2	5	4	3
32.....	π Dra	A2	o	I-2	o	I	I	I	I	3	I-2	2-3
33.....	73 Dra	A2p	o	I	2	I	2-3	I	I	5	I-2	3-4
34.....	a Cyg	A2p	I	6	o	5	I	I	I	I-2	I	8
35.....	$48^\circ 3390$ Cyg	A3	o	2-3	o	2	2-3	I-2	I-2	4	3	4
36.....	32 Aqr	A3	o	I-2	I	I	2-3	2-3	I-2	3-4	2-3	3-4

TABLE X—Continued

	4435	Mg^+ 4481	Ti^+ 4501	Fe^+ 4508	Fe^+ 4522	Fe^+ Ti^+ 4540	Cr^+ 4558	Ti^+ 4563	Ti^+ 4572	Meas. 4205	Lab.— Star	Meas. 4129	Lab.— Star
1.	o	3-4	1	1	1	3	2-3	1	1	4205.16	-11		
2.	o	4-5	2	1	1-2	3	1	1	1	4204.92	+13		
3.	o	1	1	o	1	1	o	1	1	4205.18	-13		
4.	o	5	1	1	1-2	3-4	1	1	1-2	4205.18	-13		
5.	o	4-5	1	1	1	3	1	1	1	4204.99	+6	4129.67	+7
6.	o	4	1-2	1-2	1	3-4	1	1	1	4205.09	-4		
7.	1	4	2	1-2	2-3	4	1-2	1	2	4205.01	+4	4129.80	-7
8.	1	4	1-2	1	1-2	3-4	1-2	1	2	4205.11	-6		
9.	o	2	1	o	o	1	1	1	1	4205.20	-15		
10.	1	4	2	1	2	4	1	1	2	4205.15	-10		
11.	o	8	2-3	2-3	3	5	2-3	2-3	3	4205.08	-3	4129.69	+4
12.	o	4	2	1	1-2	3-4	1	1	2	4205.07	-2		
13.	o	4-5	2	1	2	3-4	1	1	2	4205.10	-5	4129.55	+18
14.	o	4	1-2	2	1-2	4	1	1	1-2	4205.10	-5		
15.	o	4	1-2	2	1-2	3	1	1	2	4204.98	+7		
16.	o	4	1	1	1	3	1	1	1	4205.08	-3		
17.	1?	5	1-2	o	1	3-4	3-4	1	1	4205.14	-9		
18.	o	6-7	2	2	2	5-6	4	1	1-2	4205.08	-3		
19.	2	4-5	1-2	1	2-3	4-5	2	1-2	2-3				
20.	o	4-5	1	1	2	4	2-3	o	1				
21.	1?	4	1	1	1	3-4	3	1	1	4205.10	-5	4129.85	-12
22.	2	2-3	1	1?	3	4	1	1	1-2	4205.07	-2	4129.91	-18
23.	o	4	1	1?	2	4-5	4	1	1				
24.	o	5	1	1?	1	3	3	1	1	4205.20	-15	4129.52	+21
25.	1?	5	2	2	2-3	4-5	1-2	1	2	4205.14	-9	4129.57	+16
26.	o	4-5	2	1-2	2-3	4	1	1	2-3	4204.94	+11		
27.	1	6	3	3	3	5	3	2-3	3	4204.96	+9		
28.	4	1	1	1	1	3-4	1-2	1	1	4205.02	+3	4129.60	+13
29.	1	5-6	1-2	1-2	1-2	4	1-2	1	1	4205.25	-20		
30.	1	5	2	2-3	2-3	4	2	2	2-3	4204.92	+13	4129.75	-2
31.	2	5	1	1	1	2	1	1	1	4204.81	+24	4129.62	+11
32.	o	5	1-2	1-2	1	3	1-2	1	1-2	4204.98	+7		
33.	o	5	2	1	1	3-4	4	1	1	4204.88	+17	4129.75	-2
34.	o	8	3-4	5	5	6-7	5	2-3	3-4	4204.99	+6		
35.	o	5	2	1	1-2	4	1-2	1	1	4205.21	-16		
36.	1	3	2	1-2	1-2	4	2	1-2	2-3	4205.01	+4	4129.53	+20

TABLE XI

STRONGEST LINES OF V^+ IN REGION OF STELLAR SPECTROGRAMS

λ	Int. (Lab.)	Int. Disk	Int. Spot	Iden.	E.P.
4005.712.....	60	3	1	V^+	1.809
4023.376.....	50	3	2	V^+-Co	1.797
4035.022.....	40	2	1	V^+	1.785
4183.428.....	35	2N	1	V^+-	2.041
4202.34.....	35	oNd?	o	V^+	1.696
4205.087.....	30	1	*	V^+	{ 1.678 2.027

* V^+ 4205.087 is blended with Eu^+ 4205.036 in sun-spot spectrum. The blend is given by Rowland as intensity 2.

The only one of the three strongest lines that is unblended in A-type stars is λ 4023. The intensity of this line was therefore estimated on all of the plates. If λ 4023 was found to be absent, it

seemed safe to conclude that V^+ can make no sensible contribution to the stellar line at $\lambda 4205$.

The strong Eu^+ line at $\lambda 4129$ seems to be entirely unblended in A-type stars.

It thus seems that a rather definite decision can be reached concerning the presence or absence of Eu^+ from the evidence of the two strongest lines of the element at $\lambda 4129$ and $\lambda 4250$.

For two of the stars in Table X there is evidence of another sort. The variation in intensity of these lines in α^2 Canum Venaticorum and in B.D. $-18^\circ 3789$, together with the agreement in wave-length, makes the evidence overwhelming. In the case of $-18^\circ 3789$ there is no calcium line at $\lambda 4435$, and the europium line at that position varies in phase with $\lambda 4129$ and $\lambda 4205$. The spectra of the rest of the europium stars were examined for possible variability of the spectral lines. In a few cases where a number of plates was available the evidence was negative, but in most instances the data were not sufficient to make a final decision. It is possible that $\lambda 4205$ varies in intensity in 73 Draconis.

It seems that the identification with europium is certain in the case of all of the stars in Table X which contain both $\lambda 4129$ and $\lambda 4205$ and which do not contain vanadium. In only two cases where $\lambda 4129$ and $\lambda 4205$ occur is the line $V^+ 4023$ present. In Sirius $\lambda 4023$ is equal in intensity to $\lambda 4205$. The evidence for the presence of Eu^+ would be unconvincing were it not for the fact that there is a very faint line agreeing in position with $Eu^+ 4129$. Because of the coincidences of the two lines it seems probable that europium is present in Sirius. In ζ Lyrae, $\lambda 4205$ is a rather strong line, while $V^+ 4023$ is certainly weaker. $\lambda 4129$ is stronger than in α Canis Majoris, and it seems practically certain that Eu^+ is present. For the other twelve stars containing both $\lambda 4129$ and $\lambda 4205$, the identification with europium seems certain since vanadium is absent.

In the case of the stars in which only $\lambda 4205$ seems to be present, the evidence cannot be as conclusive. Several stars can be at once eliminated. α Cygni, the only supergiant in Table X, clearly does not contain europium, since the line at $\lambda 4205$ is weaker than $V^+ 4023$, and is thus probably entirely due to vanadium. In B.D. $+25^\circ 3246$

Herculis the two lines are about equal in intensity, and it seems probable that $\lambda 4205$ can be again explained by the presence of vanadium. In ϵ Serpentis, $\lambda 4205$ is possibly slightly stronger than $V^+ 4023$. It is impossible to decide with certainty, but it seems probable that europium is not present. The same reasoning applies to α Geminorum. In the case of ϵ Ursae Majoris, the only other star found to contain $V^+ 4023$, $\lambda 4205$ seems to be definitely stronger than the vanadium line. For this reason it seems that the star can be classed with the last group: those which show $\lambda 4205$, but in which both $\lambda 4129$ and $\lambda 4023$ are absent. Of this group all that can be said is: (1) The line at $\lambda 4205$ agrees within the errors of measurement with the strongest line of Eu^+ . (2) The presence of the line cannot be accounted for by any other element but europium. (3) The A stars containing $\lambda 4205$ form a related group in temperature and pressure. (4) The stars containing $\lambda 4205$ alone have spectra similar to those containing both $\lambda 4129$ and $\lambda 4205$. (5) The ratio of intensity $4129/4205$ is such that, except in one case, the faintness of $\lambda 4205$ would preclude the probability of seeing $\lambda 4129$. The single exception to this rule is 40 Aurigae, in which $\lambda 4205$ is of intensity 3, while $\lambda 4129$ seems to be absent. It seems that this may possibly be accounted for by the fact that the star is a spectroscopic binary with double lines, and estimates were possible only on the one plate which showed single lines. In connection with (3), estimates of the widths of $H\gamma$ and $H\delta$ were made to afford some idea of the range in pressure among the stars. The progressive broadening of the hydrogen lines with increasing pressure, due to Stark effect, serves as a valuable criterion of absolute magnitude. Because of the varying density of the plates, only a rough estimate was possible, but this was sufficient to show that the stars are all of the same order of absolute magnitude. On the scale adopted, the H lines in Sirius are of width 7, while those in α Cygni were estimated 1. All of the stars believed to contain europium had estimates for line-width varying from 3-4 to 6 with the exception of ζ Lyrae, which was classed 3. This definitely excludes all supergiants and makes it seem probable that the europium stars are similar to other A-type stars in general as far as pressure is concerned. It is possible that the dispersion would be much less if plates of comparable density were available.

It thus seems fairly certain that Eu^+ is present in the thirteen stars listed in Table X which show the two strongest europium lines, and highly probable for the seventeen others in which the intensity of $\lambda 4205$ cannot be accounted for by vanadium.

A rather striking similarity was observed between the behavior of chromium and europium. Every star in the range A0-A3 in which the lines of ionized chromium are strong was found to contain either one or both of the strongest lines identified with europium. In the case of B.D. - 18°3789 it has been shown that the chromium lines are variable in intensity in phase opposite to that of the europium lines. The estimates of intensity of the strongest Cr^+ line at $\lambda 4558$ is given in Table X. In such stars as 17 Comae, 78 Virginis, μ Librae, and 73 Draconis, it is equal in intensity to the outstanding Fe^+-Ti^+ 4549, and it is well marked in the majority of the stars. If the equality of $Ca-Fe$ 4227 with Fe^+-Cr^+ 4233 be taken as a criterion for spectral class A2, then all of the A stars suspected of containing europium lie within the narrow range A0-A2.

The mean of the thirty determinations of wave-length of $\lambda 4205$ in the stars is 4205.057 Å, with a probable error of ± 0.012 Å, while the laboratory value is 4205.046 Å. The mean of the thirteen measures of $\lambda 4129$ is 4129.69 Å, with a probable error of ± 0.024 Å, while the laboratory wave-length is 4129.73. The agreement is as good as can be expected. The silicon doublet $\lambda 4128$ and $\lambda 4131$ was used for the determination of the wave-length of $\lambda 4129$, while the following lines were used in the case of $\lambda 4205$: Fe^+ 4179, Fe 4202, Sr^+ 4215, and Fe^+-Cr^+ 4233.

The ionization potential of europium is not known, but from analogy to the other rare earths it seems rather safe to say that it lies between 6 and 7 volts. The intensity of the europium lines in A-type stars is thus even harder to understand, as the maximum intensity of the first stage of ionization should be much lower in the temperature scale. It is of some interest to note that the europium stars occur immediately below the "manganese"¹ stars in effective excita-

¹ In my study of the "manganese" stars (*Astrophysical Journal*, 73, 104, 1931) the stage of ionization* was found to be probably the second (Mn^{++}). Professor H. N. Russell has suggested that the lines probably arise from the singly ionized atom (Mn^+).

tion. The manganese stars are found among spectral classes B8, B9, and the high-temperature A0 stars. The A-type europium stars occur in the low-temperature A0 stars and in A2 and A3. It seems that since the segregation of these two groups of stars it should be possible to take another step toward the physical classification of the A-type stars.

YERKES OBSERVATORY

WILLIAMS BAY, WIS.

August 25, 1931

